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Biomanager Optimization Model for Enhancing Biogas Production from Cattle Farming in a Circular Economy System

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Energy access remains a challenge in rural Ecuador, where agricultural farms have modest but unmet energy needs. Traditional cooking methods depend on liquefied petroleum gas and firewood, contributing to deforestation and poor air quality. The general objective of this study is to design and implement a biodigester model to produce biogas from cattle waste, capable of satisfying the thermal energy needs of a rural farm in the Orellana Province located in Ecuador. To make up for renewable energy scarcity in rural regions, a cracking opportunity is presented that will create connectivity and diminish dependence on gird us robotics. Technical considerations were retention time, digester volume, and daily collection of manure. A baseline study of energy needs at the farm was conducted resulting in a design that can create 5 m³ of biogas/day. A 26 m³ digester was used, and the system demanded 312 kg of fresh manure each day. Biogas was consumed as a fuel source based on cooking, refrigeration and light demands. The biodigester managed to produce enough biogas to replace conventional energy sources. The annual substitution potential of the system was found to be 1.09 tons of liquefied petroleum gas, 2.37 tons of firewood and 4.38 MWh of electricity. It also decreased greenhouse gas emissions, saving 37.8 tons of CO_2 equivalent annually. The use of this technology also produced biol, an organic fertilizer that helps increase agricultural productivity, thus promoting farm sustainability. Biogas is presented as a renewable energy source available to rural farms in the study. We believe that the widespread implementation of biodigesters in Orellana could greatly improve energy security, environmental sustainability, and rural livelihoods. This underscores the importance of policies and incentives that support the adoption of biogas technology in agricultural communities. policies, for instance, to lower unemployment in economic downturns.
Keywords: GHG emission, bioenergy, biodigester technology, clean energy, cattle manure, rural development .

INTRODUCTION

Agriculture is responsible for a significant share (30−35%) of global greenhouse gas emissions, with livestock farming contributing up to 80% of these emissions (Boer IJM *et al.,* 2011; Mazzetto *et al.,* 2015; Li and Mupondwa, 2018; Schwarz *et al.,* 2022). The rising global demand for energy, largely satisfied by coal, natural gas, and oil (accounting for 75-85% of energy needs), is facing sustainability challenges due to the exhaustible nature of these resources and their environmental impact (Ramirez-Llodra *et al*., 2011; Tedeschi *et al.,* 2020; Alshawaf *et al.,* 2021). This creates an urgent need to find alternative energy solutions (Vargas-García *et al.,* 2021). Furthermore, livestock waste, such as manure, poses environmental and health risks, contaminating groundwater and releasing pollutants that degrade ecosystems through processes like eutrophication, while also contributing to soil salinization and fertility loss (Díaz-Vázquez *et al.,* 2020; Czubaszek *et al.,* 2022).

One approach involves utilizing organic waste to produce biofuels, such as biogas, which are renewable energy carriers. Biofuels (biodiesel, bioethanol, biomass, biogas)

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offer sustainable, renewable, environmental, green energy alternatives that contribute to carbon gas emission mitigation and decreased dependency on nonrenewable resources (Pérez Rincón *et al.,* 2017; Casanova *et al*., 2022; Ponce *et al.,* 2022). Biogas is a product of anaerobic digestion that converts organic matter into methane-rich gas, allowing for the production of clean energy from inputs that would otherwise create pollution (Wang, 2010; Fan *et al.,* 2018; Szymańska et al., 2022).

Countries in Asia and parts of Europe, such as China, India, and Nepal, have been advancing in biodigester technology (Preston, 2008; Ruíz *et al.,* 2024), with some Latin American countries like Cuba and Mexico adopting biogas initiatives to enhance sustainable energy use in rural areas (Srinivasan *et al.,* 2014; Venegas Venegas, 2019; Jana, 2022). In Ecuador, however, household-level biogas production remains limited, especially in rural zones where firewood is often used for cooking, contributing to deforestation and adverse health effects from smoke inhalation (Subramanian *et al.,* 2010; Priya *et al.,* 2021). Despite its many cow ranches, Joya de los Sachas canton lacks energy alternatives like biogas production, which might improve environmental management.

In Ecuador, Bioenergy has been promoted by law as an environmentally friendly energy source capable of meeting energy demands as a renewable energy option that maintains natural resources (Neethirajan, 2024; Ponce *et al.,* 2022). Considering that Orellana has an agrarian economy, bioenergy can play a key role in sustainable development for the region (Torres *et al.,* 2018; Vargas-García *et al.,* 2021). This technology can play an essential role in improving energy access in such vulnerable communities, enabling cooking, heating, lighting and refrigeration, as well as devoting less attention to energy access with traditional power sources. In Ecuador, there are few biodigesters operating, but current research aims to improve the production of biogas and biofertilizer (Rupf *et al.,* 2017; Guerrero-Pincay *et al.,* 2023; Guamán-Rivera *et al.,* 2024), as well as develop integrated systems that maximize food and energy security for farms. The objective for this study is to develop an optimal biodigester model that is capable to produce biogas, by using cattle waste, to cover the thermal energy demand at Joya de los Sachas (Orellana Province). This practice could help lessen reliance on wood and various other nonrenewable energies which support the conservation of sources as well as shield the surroundings.

MATERIALS AND METHODS

***Study location*:** The program is hosted on a rural farm in Veinticinco de Diciembre community, Tres de Noviembre parish, Joya de Los Sachas canton, Orellana, Ecuador Rumipamba is north, Lago San Pedro and Enokanki are south, San Pedro de los Cofanes of Shushufinfi is east, and Enokanqui of Joya de los Sachas is west (Salazar, 2023). This farm heats food with 30 kg of LPG and wood sometimes. They use candles for night lighting and refrigeration to preserve milk and other food products because they don't have power (INEC, 2012).

From the deductive approach (Hernández Vergel *et al.,* 2010), the study studied the topic and general theories on energy and environmental management of bovine residuals. Cow residuals could be used for energy in rural Ecuador's Orellana region to conserve resources. Reduce greenhouse gas emissions with exhaustible resources. The descriptive research begins with the farm's residual biomass potential and energy demand, then sizes the technology. The bibliographic review of scientific publications, manuals, books, and laws on bovine residual energy utilization, biogas production, and environmental impact was used as study methods. Biogas generation, energy, and environmental impacts from usable bovine residuals were calculated using statistical analysis (Mascher *et al.,* 2017). Calculations and equations were based on the 2008 German Technical Corporation GTZ design guide and installation manual for family biodigesters (Hueneburg and Hueneburg, 2013) and the authors' works (Bustamante-Lara *et al.,* 2019). The study uses first-degree equations to calculate the daily quantity of usable bovine waste, biogas production, energy generation, and CO2 avoided equivalent (Castro Morales and Rodríguez Gámez, 2022; Castro-Cedano, *et al.,* 2023). A shovel, 20-liter bucket, and hook weight were used to calculate the quantity of energy residuals from agricultural manure collected and weighed daily in the stable.

***Initial data*:** Urine, food remains, plant or animal waste, undigested food, digestive tract bacteria, digestive fluids, and water make up 80–85% of manure. From midway. Methane CH4 and carbon dioxide CO2 in biogas contribute to global warming. The global warming potential of CH4 is 21 times that of CO2. According to Adilson *et al.* (1996), Machado *et al.* (2022), and Schwarz *et al.* (2022), efficient methane collection and combustion protect the atmosphere and environment. The equivalent CO2 averted from the sanitary landfill's energy usage can be measured. This work explored the following equivalences: retention period (TR) computed for the study at 30-35°C (35 days); each cattle head can produce 40–45 kg of manure daily. In the semi-stalled regime, 22%–25% of cattle dung can be used to make biogas (8.8 kg-9.9 kg per day);

1 kg fresh manure (EF) = 0.20 kg of total solids (ST);
1 kg total solids (ST) = 0.8 kg of volatile solids (SV);
1 kg total solids (TS) = 0.08 m3 of biogas (35°C);
1 m3 biogas is equivalent to 1.3 kg of wood;
1 m3 biogas is equivalent to 0.65 l of gas oil;
1 m3 biogas is equivalent to 0.6 m3 natural gas;
1 m3 biogas is equivalent to 0.7 kg of coal;
1 m3 biogas is equivalent to 2.4 kWh.

RESULTS AND DISCUSSION

***Biomass potential derived from cattle breeding on the studied farm*:** Daily organic waste production per head of cattle averages 40 kilos. These can be harvested 8.8–9.9 kg per day in semi-stalled raising. 2011) Table 1 shows weekly stable manure measurements.

Table 1. Daily load of manure in the barn.

Weekdays	Cattle	Cattle manure (kg)	Daily manure load (kg)
Monday		9.22	331.8
mars		8.95	322.2
Wednesday		9.60	345.6
Thursday	36	9.12	328.2
Friday		9.60	345.6
Saturday		8.91	320.6
Average		8.93	321.3

The barn receives the greatest manure, 320.6kg, on Saturday and 345.6kg on Wednesday and Friday, ready for collection. The study considered 320.6 kg of manure as potential daily biomass.

***Study and definition of demand*:** In designing an appropriate biomanager, demand specification is crucial. Six people live on a farm with a rustic house without power. A monthly 30 kg tank of liquefied petroleum gas from the local commercial network is used to cook and prepare food. Table 2 illustrates biogas daily demand. From the statistics above, we learned that the farm needs 5m^3 of biogas every day.

***Definition of the biomass required to satisfy the demand*:** We calculated the useable biomass needed to produce 5 m3 of biogas per day using 0.20 kg of total solids per kilogram of fresh manure and 0.08 m3 of biogas at 35°C per kg of ST (Missanjo *et al.,* 2011). Equation 1 estimated the fresh manure needed to produce 5m^3 of biogas every day.

$$CEFNd = NBd.\,EefST.\,EstBP$$

$$CEFNd = \left(\frac{5\,m^3}{1\,day}\right)\left(\frac{1kg}{0{,}20kg}\right)\left(\frac{1kg}{0{,}08m^3}\right)$$

$$CEFNd = 312kg\ day \quad (1)$$

Where: CEFNd = amount of fresh manure needed daily (kg/day); NBd = daily biogas production requirement (5 m3/day); EefST = fresh manure equivalency per total solids (1kg EF/0.20 kg ST); EstBP = equivalence of total solids per biogas produced (1kg ST/0.08m3 BP)

Daily fresh manure needs are 312.5 kg, which can be retrieved in the stable together with EF. Table 1 shows this. Since bovine residuals include equal amounts of water and CEFNd, the total volume was calculated once the requisite manure was determined. Thus, 625 kg of mix is charged per day.

***Bioreactor design*:** After analyzing the bioreactors' techno-energetic characteristics, demand, and case study, a Chinese-made fixed dome biodigester was found practical. The bioreactor with a fixed dome has a brick, stone, and concrete gas chamber and a straight-sided hemispherical lid. The interior surface is protected with thin layers for durability and waterproofness. An inspection plug on top of the dome allows cleaning. Gas from digestion is trapped in the dome or gas chamber at 1m to 1.5m water column pressure. Without a gas container, this technology's structural force creates the dome's hemispherical shape. As gas volume increases in the dome, pressure can exceed 100 cm of water column. Quality materials and methods are needed during building. Although Ecuador has not adopted the technology, more than 5 million bioreactors in China have been built using the knowledge obtained during these devices' manufacture. The Chinese fixed dome bioreactor produces biogas at 0.5–1 volume per digester volume at temperatures over 30°C. Figure 2 shows a cross-sectional diagram of the Chinese fixed-dome bioreactor to be designed. A cross-sectional diagram of the Chinese fixed-dome bioreactor under design is shown in Figure 2.

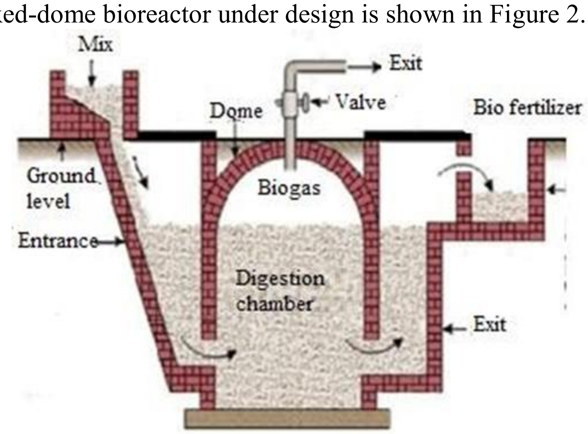

Figure 1. Cross-sectional diagram of the Chinese fixed-dome bioreactor.

Table 2. Daily biogas demand.

Device	Amount	Nominal biogas consumption (L/h)	Working hours in a day (h)	Total biogas demand (L)
Kitchen	1	267	5	1.335
Mantilla lamp	4	150	4	2.400
Refrigerator (100 mL)	1	60	20	1.200
Total	7	510		4.935

***Total volume (Vt) of the bioreactor tank*:** The bioreactor tank's volume was determined using a retention duration of 35 days and a daily load (CD) of 625 kg mix (0.625m3/day). Vt of the biodigester tank was calculated using equation 2.

$$Vt = CD.TR$$

$$\text{Vt} = \frac{0.625m3}{1\,day}\,(365\text{ days})$$

Where: VT = total volume of the biodigester tank (m^3); CD = daily load (0.625m3/day); TR = holding time (35 days); The total volume of the biodigester tank is $22m^3$.

***Bioreactor diameter*:** Comprehend the biodigester tank's Vt to determine the vertical well's depth. The diameter (Ø) of this cylindrical biodigester is equal to the depth (H). Equation 3 is used for this.

$$Ø = H$$

$$Vb = \left(\frac{\pi Ø^2}{4}\right)(H)$$

Where:

$Vb \rightarrow$bioreactor volume

replacing$H$ by$Ø$

$$Ø = \sqrt[3]{\frac{V.4}{\pi}}$$

Replacing by their values

$$Ø = \sqrt[3]{\frac{22m^3.4}{3.1416}}$$

$$Ø = \sqrt[3]{28.03}$$

$$Ø = 3m$$

The diameter of the biodigester is*3m.*

***Biodigester height (H)*:** The calculation of the depth for the biodigester of 22 m^3 of volume, if Ø=3m, begins with the fact that the well's height relation is not always 1 to 1. Equation 4 was used to determine the device's height.

$$Vb = \left(\frac{\pi Ø^2}{4}\right)(H)$$

$$Vb = \left(\frac{Pi.(3m)^2}{4}\right)(H)$$

$$H = 3{,}10m$$

If a free edge of 20 centimeters is left, then the total height will be:

Hb= total height of biodigester

$$Hb = H + 0{,}20m$$

$$Hb = 3.30m$$

The height of the biodigester is 3.30m.

***Computation of the dome's curvature*:** quation 5 was used to calculate the curvature of the dome (f1), considering the bioreactor's dimensions (Ø=3m) and the device's overall height (Hb=3.30m). F1 in the upper house:

$$f_1 = \left(\frac{1}{5}\right) Ø$$

$$f_1 = 0{,}2\,.\,3m$$

$$f_1 = 0.6m$$

The curvature of the dome is0.6m Bioreactor radius (r):

To calculate the radius of the bioreactor, equation 6 was applied.

$$r = \sqrt{\frac{Vb}{Pi\,.Hb}}$$

$$r = 1{,}50m$$

The radius of the bioreactor is 1.50 m.

Radius of curvature of the upper sphere (R1):

To calculate the radius of curvature of the upper sphere, equation 7 was applied

$$R_1 = \frac{(r)^2 + (f_1)^2}{2f_1} = \frac{(1{,}51)^2 + (0.6m)^2}{2(0.6m)}$$

$$R_1 = 2.20\text{m}$$

The radius of curvature of the upper sphere is 2.20m.

Dome volume (IN1)

$$IN_1 = p(f_1)^2\left(R_1 - \frac{f_1}{a}\right) \quad (8)$$

$$IN_1 = 3{,}142\,.\,0{,}36m\,(2{,}20m - \frac{0{,}60m}{3})$$

$$IN_1 = 2{,}26m^3$$

To calculate the volume of the dome, equation 8 was applied.

Where: a ↔ a constant.

The volume of the dome is $2{,}26m^3$. Cylinder volume (IN2):

$IN1 = 2.26\ m3$

Equation 9 was used to calculate the volume of the cylinder.

$$IN_2 = \pi\,.\,r^2\,.\,Hb$$

$$IN_2 = 23.6m^3$$

The volume of the cylinder is 23.6 m^3.

Total volume of the bioreactor (Vfb):

Equation 10 was used to calculate the total volume of the bioreactor

$$IN_{fb} = IN_1 + IN_2$$

$$IN_{fb} = 26m^3$$

The total volume of the bioreactor is 26 m^3.

Summary of bioreactor technical parameters

Table 3 shows a summary of the technical parameters of the bioreactor

Table 3. Summary of technical parameters

N°	parameters	Symbol	Value	Unit
1	tank volume	Vt	22	m3
2	Diameter	Ø	3	m3
3	Height	Hb	3.30	m3
4	Dome (dome) curvature	f1	0,6	m3
5	Radio	r	1.50	m3
6	Radius of curvature of the upper sphere	R1	2.20	m3
7	Dome (dome) volume	V1	2.26	m3
8	cylinder volume	v2	23.6	m3
9	total volume	Vfb	26	m3

***Bioreactor construction cost analysis*:** The financial constraints of cattle-raising farms are one of the barriers to the adoption and widespread use of biodigesters to produce biogas. Table 4 displays the approximate cost of building and implementing a biodigester that can produce 5 m3 of biogas per day.

Table 4. Estimated cost of building a bioreactor.

Expense detail	Amount	Unit price USD	Total price USD
Excavation (m3)	158	3.1	489.8
Wall formwork (m2)	44	5.97	262.68
Dome formwork (m2)	17	5.97	101.49
Reinforcing steel (kg)	98	3.15	308.7
Welded Mesh (kg)	61	3.64	222.04
Plain concrete (m3)	12	81.77	981.24
Base paving (m2)	6	9.59	57.54
plaster wall (m2)	61	9.56	583.16
Stuffed (m3)	29	2.17	62.93
Provision and placement of PVC pipes ½ (m)	51	2.63	134.13
Total			3203.71

Our growing awareness of the energy and environmental importance of producing and using biomass from cattle rearing for biogas development and energy use allowed us to assess the study's goals' viability. Energy includes environmental and social factors. Bioreactors for livestock waste in rural areas have advanced technologically and acquired space, as reported by CEPAL (2019) in 2014 (Bragulat *et al.,* 2020; Castro Morales and Rodríguez Gámez, 2022).

Rural Ecuador has significant biomass potential and energy needs, but biogas production technology utilization is limited, particularly in Orellana province (Neugebauer, 1988; Lambin and Meyfroidt, 2011; Vargas-García *et al.,* 2021). Experts recommend that farmers and rural households prepare and cook food, refrigerate milk and other food products, and have appropriate lighting (FAO, 2019).

Using findings from Castro-Bedriñana *et al.* (2022) and Muñoz *et al.* (2020) research. Pérez *et al.* (2017) gave indicators to simplify job calculations. The farms in Orellana have 30–60 cattle (Guaman-Rivera, 2022; Guamán Rivera *et al.,* 2023). The case study was placed on a 36-bovine farm. The authors found that 321 kg of manure can be recovered from the stable daily, producing 5 m^3 of biogas that can be used for cooking, refrigeration, and night lighting with biogas lamps.

In addition to producing 0.6 m^3 of biol, a high-organic fertilizer that can benefit the farm's crops for self-consumption, the Chinese-designed fixed-dome bioreactor produces 5 m3 daily to meet the farm's needs. The Chinese type of bioreactor has the following advantages: its design ensures a reasonable distribution of basic constraints; it is developed underground, so it has little space; the necessary materials are available in the local showcase; and with proper management, it can last up to 20 years.

A crucial inferred generation of biofertilizer with a tall natural material benefits agrarian generation and biogas, and decreasing CH_4 to the environment is a natural advantage. Compared to other vitality structures, it offers a moo development and get-together taken toll; operation and maintenance are straightforward and well-adapted by the client.

One drawback is the establishment's daily consideration of stacking the fertilizer mix to be prepared and the biol to be put away to avoid bioreactor outlet impediments. Assuming the bioreactor is a continuous and persistent generation system, it may create 5 m^3 of biogas per day, 1.825 m^3 annually, 1.095 kg of melted petroleum gas, 2.372 kg of wood, and 4.38 MWh of electricity. It prevents 38.3 tons of CO_2 equivalent emissions each year.

***Conclusion*:** Once the study was conducted, we confirmed that the use of cattle breeding residues to prepare the optimized biodigester model we propose generates renewable energy, used for cooking, refrigeration and lighting in rural farms, promotes a reduction of non-renewable energy use and greenhouse gas emissions," he said. In Orellana, even though biomass from cattle breeding is available, there is no energy use; cooking is done using liquefied petroleum gas or wood and, in addition, there are places that are out of electricity that are not without refrigeration. For example, a farm with 36 cattle could produce more than 320 kg of manure every day, producing 5 m^3 of biogas—enough energy to meet its energy requirements. However, the bioreactor has a continuous supply, annually substituting 1.09 t of LPG, 2.37 t of wood, and 4.38 MWh of electricity while avoiding 1.8 t of methane emissions equivalent to 37.8 t of CO_2.

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SDGs addressed: Climate Action, Decent Work and Economic Growth, Affordable and Clean Energy.

Policy referred: Ecuador's Organic Law on the Public Electricity Service (LOSPEE); Ecuador's National Energy Agenda (Agenda Nacional Energética);Nationally Determined Contributions (NDCs).

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